

USNO ALTERNATE MASTER CLOCK STEERING

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Abstract

The primary mission of the U.S. Naval Observatory (USNO) Alternate Master Clock (AMC) facility, located at Schriever AFB, is to back up the critical functions of the USNO Time Service Department in Washington, D.C. The USNO AMC operates two Master Clocks, AMC #1 and AMC #2. Each one of these [Alternate] Master Clocks is ready to function as the nation's source for precise time, UTC(USNO), should the need arise.

This paper summarizes the current status of, and strategies used for, the steering of these Alternate Master Clocks. The various USNO AMC steering strategies utilize clock comparisons from Two-Way Satellite Time Transfer (TWSTT), GPS Common View (CV), and USNO AMC Timescale data. All current Alternate Master Clock steering strategies employ a combination of Kalman filtering and second-order control, first introduced into USNO operations in 1995. The respective designs for these steering strategies are based on several factors, including goals for synchronization and stability, as well as the desire for robustness and simplicity of operation. This paper analyzes the performance of these respective designs.

INTRODUCTION

As the criticality of precise timing to the security and economy of the United States increases, so does the need for robustness in the quality and availability of precise time. The United States Naval Observatory (USNO) must ensure its ability to provide a stable, continuous source of precise time for the nation. Key to ensuring the continuity of such operations is the USNO Alternate Master Clock (AMC), located in Colorado at Schriever Air Force Base (AFB). The AMC is ready, as necessary, to assume responsibility for the critical functions performed by the USNO Time Service department in Washington, D.C., for the Department of Defense and other United States customers.

During normal standby operations, the AMC provides various time and frequency signals to several users co-located at Schriever AFB. These users include the Air Force Technical Applications Center (AFTAC), Army and Air Force Defense Satellite Communications System (DSCS) stations and other communication modules, and Network Time Protocol (NTP) customers, as well as telephone modem and voice users. Additionally, the AMC provides an extremely stable 5 MHz reference to the GPS monitor station in Colorado Springs, as well as technical consultation on timing issues to the GPS community at Schriever AFB [1].

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For clarity this paper will refer to the USNO facility located in Washington, D.C. as USNO, and the Alternate Master Clock facility as AMC.

AMC CLOCKS/TIMESCALES

As part of fulfilling the above missions, the AMC operates two Master Clock systems, AMC#1 and AMC#2. Each system uses an input 5 MHz signal from independent hydrogen maser frequency standards, and receives digital frequency steering commands. The current primary Alternate Master Clock is AMC#1, which is steered to UTC(USNO) in Washington, D.C. using hourly Two-Way Satellite Time Transfer (TWSTT) measurements (when available).

The AMC also maintains and operates various mean timescales, based on phase measurements from up to three hydrogen masers and up to 12 cesium frequency standards. Many of the AMC mean timescales are analogous to those residing at USNO, though with substantially less contributing frequency standards. In particular, the AMC maintains a cesium-only mean (#203), a maser-only mean (#198), and a “dynamic” mean that weights masers higher in short-term, and cesiums higher in long-term, through continuous, hourly recomputation (#200) [2]. The AMC also maintains steered versions of these means, (#204, #199, #202, respectively) which are synchronized to the USNO counterpart means monthly.

INTERMEDIATE MEANS

Since March 1997, the AMC has also maintained separate versions of the unsteered AMC mean timescales, which the AMC can steer towards selected references. Currently, these intermediate means include hourly-steered copies of #200 (200S), and #203 (203S). 200S acts as a buffer timescale for AMC#2 disciplining, and 203S contributes to the AMC Phase Monitoring system, described later.

Since the standard AMC timescales (#198, #199, #200, #202, #203, #204), like their USNO counterparts, are designed for retroactive recomputation, they often experience phase steps in real time. Phase steps, by themselves, can potentially impact monitoring and steering functions. The AMC has designed two available remedies for this phenomenon: 1) A program to bookkeep and counter-correct such steps in the Intermediate Means 200S and 203S (in use since 1997), and 2) Operational restrictions on retroactive recomputation (in use since 1999). Both have ensured that steps in the AMC means do not impact Alternate Master Clock steering or monitoring.

STEERING CONFIGURATIONS

USNO has two current operational techniques of performing time comparisons between USNO and the AMC: TWSTT and GPS Common View (CV). With these available synchronization sources, the two Alternate Master Clock systems, and the AMC Intermediate Means, the AMC can operate under several different steering configurations.

Primary Configuration

The primary measurement for synchronizing the AMC with USNO is TWSTT. Accordingly, AMC#1 is steered to UTC(USNO) via TWSTT. AMC#2 is steered to 200S, which is, in turn, steered to AMC#1.

The Intermediate Mean 200S acts as a stable buffer between AMC#2 and AMC#1, to a) keep AMC#2 close in time and frequency to AMC#1 in a “hot backup” sense, yet b) simultaneously protect AMC#2 from overly aggressive steering in the event of a runoff in AMC#1. See Figure 1.

The AMC has operated under this Primary Configuration for the majority of time since October 1998.

Secondary Configuration

Were the AMC to lose TWSTT measurements for an extended period of time, the AMC could begin steering 200S to UTC(USNO) using CV data, and simultaneously begin steering AMC#1 to 200S. Switching from Primary to Secondary Configuration incurs no change on AMC#2’s steering target—AMC#2 is steered to 200S in both configurations. See Figure 2.

The AMC does not normally operate under this configuration for two reasons. For one, USNO’s TWSTT system currently offers superior calibration stability over USNO’s current GPS CV receiver system [3]. Secondly, since GPS is an extremely important USNO customer, using GPS CV poses a potential, though unlikely, issue of operational fidelity. One could argue that USNO should never become dependent on the service provided by one of their own customers, in order to maintain service provided *to* that customer and other customers. Were GPS to malfunction in some very unlikely fashion, the AMC would lose GPS CV, and thus, the ability to use this described configuration. For this reason and others, USNO may benefit by continuing to maintain and utilize a synchronization source independent of the GPS system, as it does today with TWSTT.

Hybrid Configuration

The Hybrid Configuration makes use of both available synchronization sources. In the Hybrid, AMC#1 is steered to UTC(USNO) using TWSTT, as in the Primary Configuration, yet 200S is steered to UTC(USNO) using GPS CV, as in the Secondary Configuration. In the Hybrid Configuration, AMC#1 and 200S are compared, but neither one is steered towards the other. See Figure 3.

The AMC operated under this configuration for the full month of August 2000. This configuration permitted a comparison between the two synchronization methods. Performance numbers are presented later in this paper, but overall the Hybrid Configuration demonstrated the inherent calibration instability USNO experiences with its current operational authorized GPS receivers. USNO is currently testing new receivers that promise improved calibration stability.

Contingency Configuration

In the unlikely event of a catastrophic or temporary loss of the Department of Defense (DoD) Master Clock at USNO, the AMC must assume responsibility for maintaining time for the nation. Additionally, in the event that the AMC loses all synchronization measurements from USNO for an extended period of time, the AMC must freewheel. Under such scenarios, the AMC can operate in the Contingency Configuration.

The Contingency Configuration steers both AMC#1 and AMC#2 to 200S, which freewheels on the available hydrogen maser and cesium frequency standards. See Figure 4.

To date the AMC has not needed to operate under the Contingency Configuration.

AMC PHASE MONITORING

The AMC Phase Monitoring system, in operation since November 1997, compares both Alternate Master Clocks to a semi-independent AMC mean timescale, namely 203S. To independently monitor two hydrogen-maser-referenced Alternate Master Clock systems using a mean timescale, the AMC must use a mean that consists of only frequency standards independent of the Master Clock systems. A suitable choice for this task is a cesium-only mean. However, since any two independent clocks systems will eventually walk off from each other, a straight comparison between the unsteered AMC cesium mean and the Master Clocks would produce differences that would be unbounded over time.

Since GPS depends greatly on stability over time spans ≤ 1 day, the AMC phase monitoring system must detect significant, short-term excursions in the Master Clocks, as opposed to absolute long-term differences between independent timescales. To facilitate the monitoring of short-term excursions, the AMC gently steers 203S to AMC#1 hourly, with a magnitude limit of, currently, 2.7 E-16 s/s . The AMC then intercompares AMC#1, AMC#2, and 203S, using majority logic, to detect if a significant excursion in one of the three is occurring. The comparisons between AMC#1 and AMC#2 utilize two independent measurement systems.

As mentioned earlier, AMC#1 currently provides an extremely stable frequency signal to the GPS monitor station in Colorado Springs. If $|\text{AMC\#1} - \text{AMC\#2}|$ and $|\text{AMC\#1} - 203\text{S}|$ both exceed 5 ns, the AMC Phase Monitoring system will generate a “NOGO” flag for GPS operators to discontinue use of AMC#1. This system is also designed to work analogously for AMC#2, during times when AMC#2 provides the 5 MHz source to the GPS monitor station. See Figure 5.

AMC#1, since it first offered service to the GPS monitor station in September 1996, has operated without disruption. As such, the AMC Phase Monitoring System has not yet needed to produce a “NOGO” flag.

STEERING-RELATED MATHEMATICS

All of the above steering and monitoring systems make use of Kalman filter state estimation, and second-order control using two-state gain vectors, derived using Linear Quadratic Gaussian (LQG) control theory. This combination first appeared operationally in a program that steered AMC#1 to UTC(USNO) using TWSTT data, in 1995. The basic second-order steering function used is as follows [4]:

$$u(k) = -G_0 x(k) \quad (1)$$

where $u(k)$ is the calculated steer command at Kalman time k , $G_0 = [g_\mu \ g_\lambda]$ is the 1×2 gain vector, and $x(k)$ is the 2×1 state estimate of phase and frequency. In essence, for each Kalman epoch k , a program multiplies the time/phase offset by g_μ and the rate/frequency offset by g_λ , and sums the results to produce a single frequency steering command for that control system, in units of seconds/second.

The matrix algebra involved in the derivation of these gains is covered in [4]. In short, designers input selected weighting matrices W_R and W_Q , into a steady-state Riccati equation to solve for G_0 , in order to satisfy a cost function:

$$J = \sum_k [(x(k)^T W_Q x(k) + u(k)^T W_R u(k))] \quad (2)$$

The message conveyed by the above cost equation is as follows: the goals of synchronization, syntonization, and stability are not mutually exclusive. That is, the desire for minimizing phase offsets, frequency offsets, and the amount of steering control used can, at best, only be **balanced**.

A rule of thumb from Applied Optimal Control [5] relates selected designer requirements/goals for phase and frequency offsets as well as steering values, to the derivation of optimal coefficients within the gain vector. This rule of thumb examines the diagonal elements of the weighting matrices used in the cost function equation:

$$W_R = [w_r] \quad (3)$$

$$W_Q = \begin{bmatrix} w_{q1} & 0 \\ 0 & w_{q2} \end{bmatrix} \quad (4)$$

Using the Applied Optimal Control approach, the authors set:

w_r = the inverse of the square of the steering magnitude goal

w_{q1} = the inverse of the square of the phase offset goal

w_{q2} = the inverse of the square of the frequency offset goal

The use of the word “goal” above is in the sense of relative maximum allowed offsets. Since continuously and simultaneously achieving zero phase offsets, zero frequency offsets, and zero use of steering is unachievable in our systems, the designer can, at best, only balance the relative, respective goals. As long as the relative “goals” are proportionate, the cost function will produce optimal gains intended to balance the respective input goals. Of course, empirical demonstration, either through simulation or safe off-line demonstration, is prudent for confirming how well the resultant gains do, in fact, achieve their respective goals. The designer must analyze the step and ramp responses of the system to ensure that the goals used have generated control gains with the desired damping characteristics and time constants.

Below is a table of the designer goals used in the respective steering algorithms described in this paper, as well as the gain coefficients produced by solving a steady-state Riccati equation. The below goals, and resultant gains, are current as of 1 October 2000. These goals are not fixed values, but rather are subject to change based on operational factors at the AMC:

| STEERING SYSTEM | Update Interval | Phase Goal | Frequency Goal | Steering Goal | Gain Matrix [1/s (unitless)] |
|---------------------------------|-----------------|------------|----------------|---------------|-----------------------------------|
| AMC#1 to UTC(USNO) via TWSTT | 3600 s | 1.90 ns | 4.00 E-15 s/s | 6.00 E-17 s/s | [3.135 E-08 0.0210] |
| 200S to AMC#1 | 3600 s | 1.50 ns | 3.00 E-15 s/s | 8.33 E-17 s/s | [5.446 E-08 0.0335] |
| AMC#2 to 200S | 3600 s | 0.90 ns | 2.00 E-15 s/s | 8.33E-17 s/s | [9.010 E-08 0.0477] |
| 203S to AMC#1 | 3600 s | 2.84 ns | 6.00 E-15 s/s | 9.00 E-17 s/s | [3.135 E-08 0.0210] |
| 200S to UTC(USNO) via CV | 86400 s | 3.00 ns | 6.00 E-15 s/s | 2.00 E-15 s/s | [5.260 E-07 0.3780] |

An important fact to note is that the AMC has, at its disposal, multiple configurations for steering AMC clocks. Often, the chosen configuration will steer clocks in a chainlike fashion. For example, currently AMC#2 is steered to 200S, which is steered to AMC#1, which is, in turn, steered to UTC(USNO). The primary advantage of the chainlike system is the inherent robustness in the event of an anomaly in one part of the chain. Impact down the chain is kept to a minimum by limiting hourly steers and by permitting the ability to freewheel if the system detects that a reference is either performing poorly or unavailable. The primary disadvantage of this chainlike approach is the potential for lesser quality steady-state performance. The tradeoff between minimizing worst-day errors vs. minimizing steady-state errors is ultimately up to the designer. The steering systems implemented at the AMC are designed around the principle, “A timing system is only as good as its worst day.”

STEERING OPERATIONS

All of the above steering designs are currently either in use, or on standby ready for use, at the AMC. The respective Kalman filters in each of the above systems employ 3-sigma outlier detection, steering limiters, and a robust advisory system that notifies operators when less-than-desired performance is detected.

Figure 6 presents AMC#1 and AMC#2 steering performance, by plotting Kalman filter estimates of AMC#1 – UTC(USNO) [TWSTT], AMC#1 – 200S, and AMC#2 – 200S. Figure 7 presents AMC Phase Monitoring performance by plotting AMC#1 – 203S and AMC#2 – 203S.

The performance of all of the above systems can potentially experience some degradation in the absence of measurements, be the measurements in the form of TWSTT, CV, or on-site measurement systems. Thanks in large part to the superb stability offered by the on-site cesium and hydrogen maser frequency standards, such degradation will usually be below the noise level required by users, during reasonable outage intervals. Figure 8 compares linear residuals of the accumulation in frequency due to the steering of UTC(USNO), AMC#1, and AMC#2, during a continuous 10-month period in 1999. The figure shows how AMC#1 and AMC#2 track the steering of the USNO Master Clock.

CONCLUSIONS

The current AMC steering programs are designed to optimally balance the goals of minimizing phase offsets, frequency offsets, and instability due to steering. Empirical performance supports the success of this design.

TWSTT is important for good USNO-AMC synchronization, though GPS CV offers an acceptable secondary source for USNO-AMC synchronization, during extensive temporary absences of TWSTT measurements.

The AMC mean timescales, like their analogous counterparts at USNO, perform excellently. The AMC intermediate mean timescales, as a result, serve very well for the functions of Alternate Master Clock disciplining, and AMC Phase Monitoring.

The steering and monitoring systems described in this paper are robust, operate automatically, and usually require no operator intervention, except when database values, such as Kalman filter noise parameter and gain coefficients, require updates.

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Primary Configuration

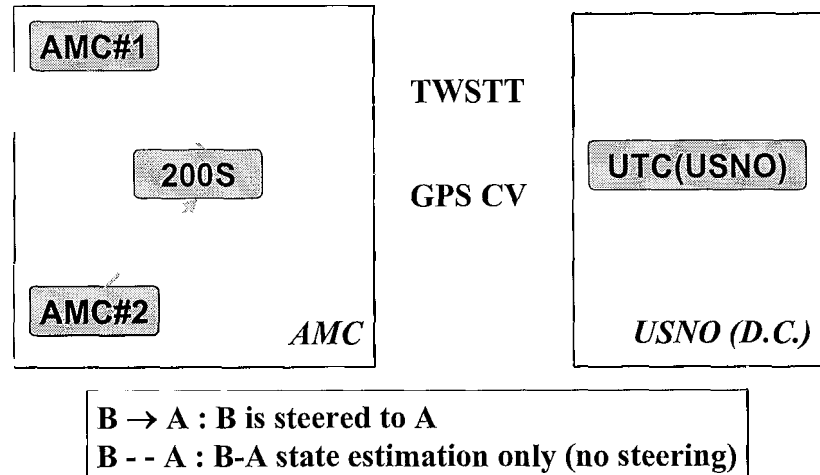


Figure 1. Primary AMC Steering Configuration

Secondary Configuration

(In absence of TWSTT)

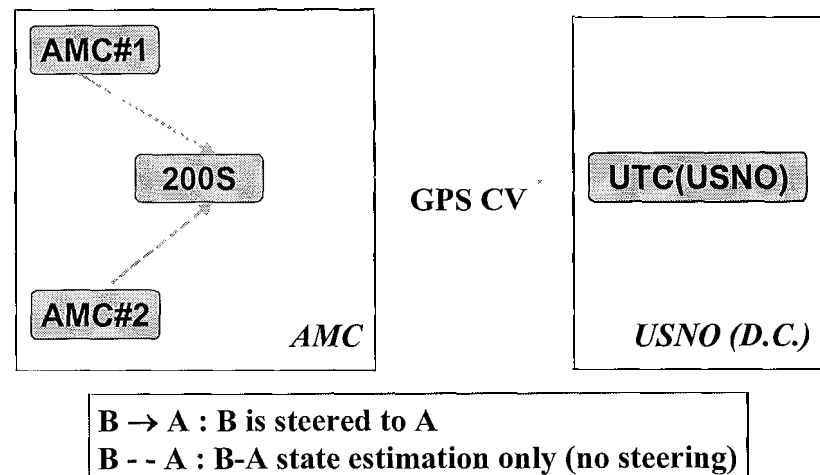


Figure 2. Secondary AMC Steering Configuration

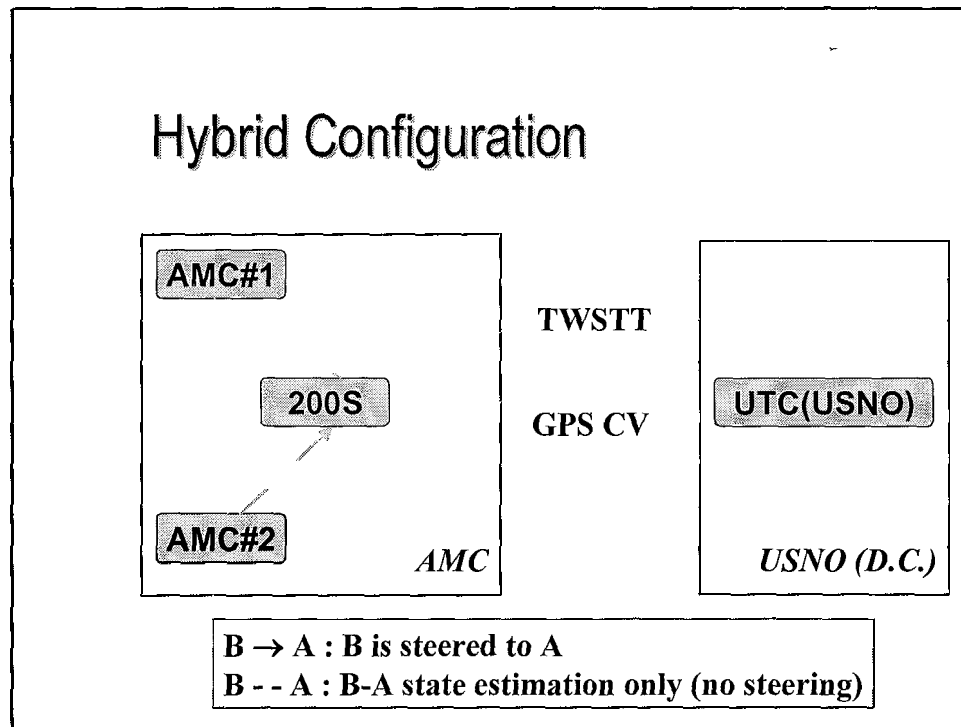


Figure 3. Hybrid AMC Steering Configuration

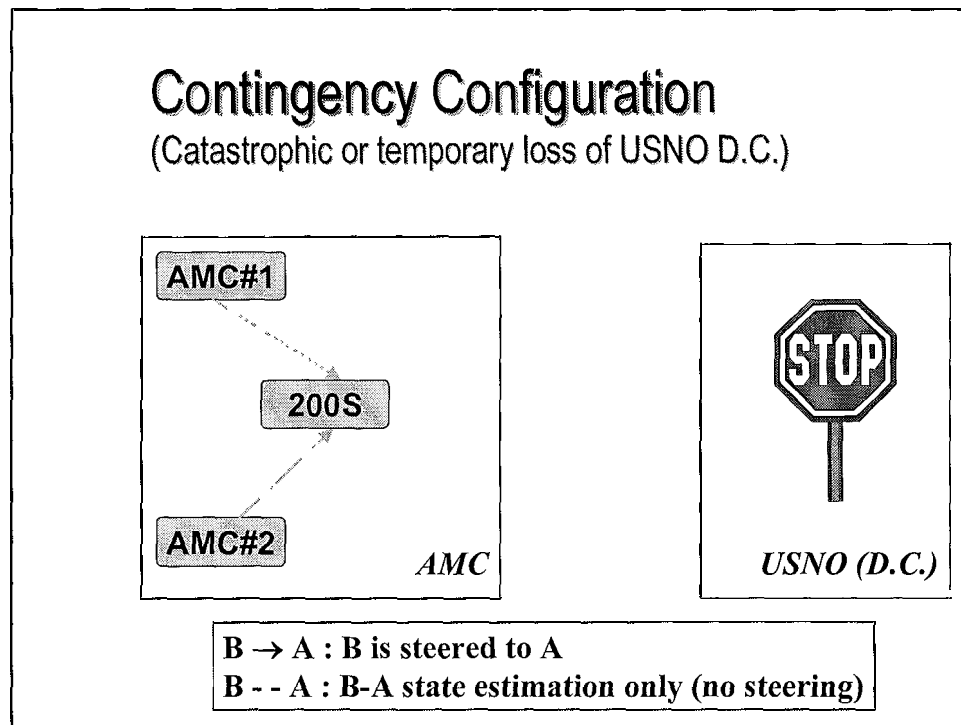
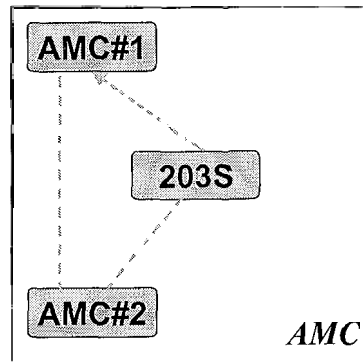


Figure 4. Contingency AMC Steering Configuration

AMC Phase Monitoring

(Current Configuration)



If
 $|AMC\#1 - 203S| > \text{Tolerance}$
 &
 $|AMC\#1 - AMC\#2| > \text{Tolerance}$
 Then
 Change AMC#1 "GO" to
 "NOGO"

B → A : B is steered to A
B - - A : B-A state estimation only (no steering)

Figure 5. AMC Phase Monitoring

AMC Steering Performance

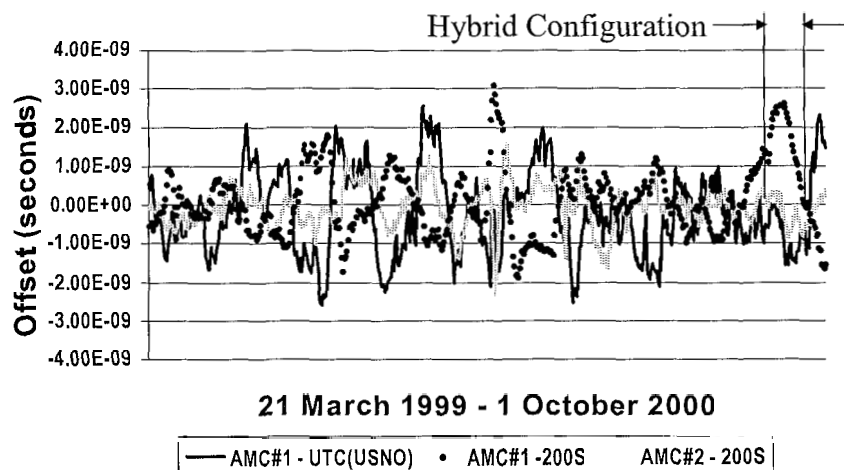


Figure 6. AMC Steering Performance

AMC Phase Monitoring System

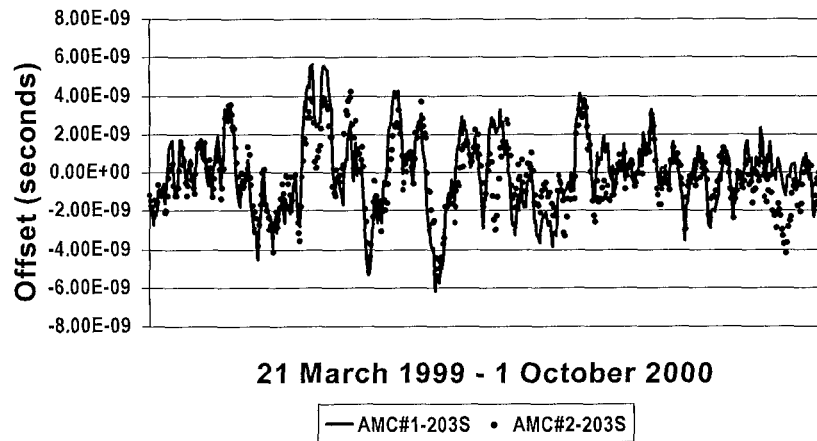


Figure 7. AMC Phase Monitoring Performance

Steering Comparison

Accumulated frequency due to steering (linear residuals)

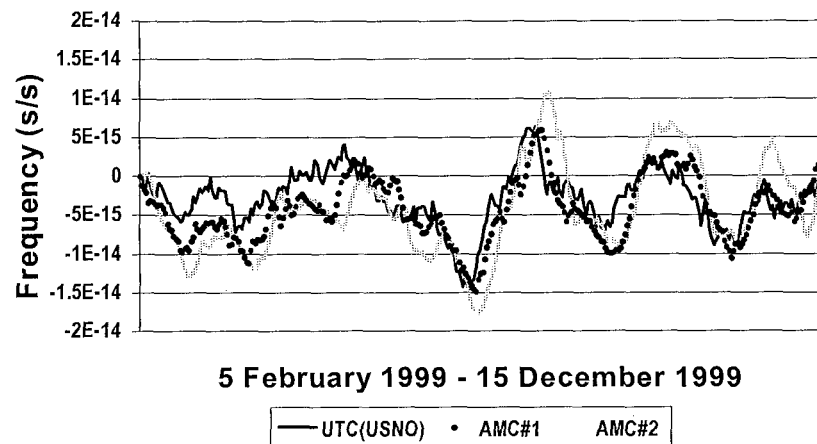


Figure 8. Clock Steering Comparison